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Artificial Chattering Free on-line Modified Sliding Mode Algorithm: Applied in Continuum Robot Manipulator

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Abstract— In this research, an artificial chattering free adaptive fuzzy modified sliding mode control design and application to continuum robotic manipulator has proposed in order to design high performance nonlinear controller in the presence of uncertainties. Regarding to the positive points in sliding mode controller, fuzzy logic controller and online tuning method, the output improves. Each method by adding to the previous controller has covered negative points. The main target in this research is design of model free estimator on-line sliding mode fuzzy algorithm for continuum robot manipulator to reach an acceptable performance. Continuum robot manipulators are highly nonlinear, and a number of parameters are uncertain, therefore design model free controller by both analytical and empirical paradigms are the main goal. Although classical sliding mode methodology has acceptable performance with known dynamic parameters such as stability and robustness but there are two important disadvantages as below: chattering phenomenon and mathematical nonlinear dynamic equivalent controller part. To solve the chattering fuzzy logic inference applied instead of dead zone function. To solve the equivalent problems in classical sliding mode controller this paper focuses on applied on-line tuning method in classical controller. This algorithm works very well in certain and uncertain environment. The system performance in sliding mode controller is sensitive to the sliding function. Therefore, compute the optimum value of sliding function for a system is the next challenge. This problem has solved by adjusting sliding function of the on-line method continuously in real-time. In this way, the overall system performance has improved with respect to the classical sliding mode controller. This controller solved chattering phenomenon as well as mathematical nonlinear equivalent part by applied modified PID supervisory method in modified fuzzy sliding mode controller and tuning the sliding function.

Index Terms— Chattering phenomenon, chattering free adaptive sliding mode fuzzy control, nonlinear controller, fuzzy logic controller, sliding mode controller, continuum robot manipulator.

I. INTRODUCTION

A robot system without any controllers does not to have any benefits, because controller is the main part in this sophisticated system. The main objectives to control robot manipulators are stability and robustness. Many researchers work on the design controller for continuum robotic manipulators in order to have the best performance. Control of any systems divided into two main groups: linear and nonlinear controller [1-10].

However, one of the important challenges in control algorithms is to have linear controller behavior for easy implementation of nonlinear systems but these algorithms have some limitation such as adjust the operating point [1]. Most of industrial continuum robot manipulators are usually controlled by linear PID controllers. But the robot manipulator dynamic functions are, nonlinear with strong coupling between joints (low gear ratio), structure and unstructured uncertainty and Multi-Inputs Multi-Outputs (MIMO) which, design linear controller is very difficult especially if the velocity and acceleration of robot manipulator be high and also when the ratio between joints gear be small [2-5]. To eliminate above problems in physical systems most of control researcher go toward to select nonlinear robust controller.

One of the most important powerful nonlinear robust controllers is Sliding Mode Controller (SMC). Sliding mode control methodology was first proposed in the 1950 [11-23]. This controller has been analyzed by many researchers in recent years. This controller has been recently used in wide range of areas such as in robotics, process control, aerospace applications and in power converters. The main reason to opt for this controller is its acceptable control performance wide range and solves some main challenging topics in control such as resistivity to the external disturbance and uncertainty. However pure sliding mode controller has some disadvantages. First, chattering problem can caused the high frequency oscillation of the controllers output. Secondly, sensitive where this controller is very sensitive to the noise when the input signals is very close to zero. Equivalent dynamic formulation is another disadvantage where calculation of equivalent control formulation is difficult since it is depending on the nonlinear dynamic equation [24-56]. Many papers were presented to solve these problems as reported in [57-69].

Since the invention of fuzzy logic theory in 1965 by Zadeh, it has been used in many areas. Fuzzy Logic Controller (FLC) is one of the most important applications of fuzzy logic theory [33-69]. This controller can be used to control nonlinear, uncertain and noisy systems. Fuzzy logic control systems, do not use complex mathematically models of plant for analysis. This method is free of some model-based techniques as in classical controllers. It must be noted here that the application of fuzzy logic is not limited only to modeling of nonlinear systems [14-32] but also this method can help engineers to design easier controller. However pure FLC works in many engineering applications but, it cannot guarantee two most important challenges in control, namely, stability and acceptable performance [18-28].

Adaptive control used in systems whose dynamic parameters are varying and need to be trained on line. Adaptive fuzzy inference system provide a good knowledge tools to adjust a complex uncertain nonlinear system with changing dynamics to have an acceptable performance [29-48] Combined adaptive method to artificial sliding mode controllers can help the controllers to have a better performance by online tuning the nonlinear and time variant parameters [30-37].

Continuum robots represent a class of robots that have a biologically inspired form characterized by flexible backbones and high degrees-of-freedom structures [1]. The idea of creating "trunk and tentacle" robots, (in recent years termed continuum robots [1]), is not new [2]. Inspired by the bodies of animals such as snakes [3], the arms of octopi [4], and the trunks of elephants [5-6], researchers have been building prototypes for many years. A key motivation in this research has been to reproduce in robots some of the special qualities of the biological counterparts. This includes the ability to "slither" into tight and congested spaces, and (of particular interest in this work) the ability to grasp and manipulate a wide range of objects, via the use of "whole arm manipulation" i.e. wrapping their bodies around objects, conforming to their shape profiles. Hence, these robots have potential applications in whole arm grasping and manipulation in unstructured environments such as rescue operations. Theoretically, the compliant nature of a continuum robot provides infinite degrees of freedom to these devices. However, there is a limitation set by the practical inability to incorporate infinite actuators in the device. Most of these robots are consequently underactuated (in terms of numbers of independent actuators) with respect to their anticipated tasks. In other words they must achieve a wide range of configurations with relatively few control inputs. This is partly due to the desire to keep the body structures (which, unlike in conventional rigid-link manipulators or fingers, are required to directly contact the environment) "clean and soft", but also to exploit the extra control authority available due to the continuum contact conditions with a minimum number of actuators. For example, the Octarm VI continuum manipulator, discussed frequently in this paper, has nine independent actuated degrees-of-freedom with only three sections. Continuum manipulators differ fundamentally from rigid-link and hyper-redundant robots by having an unconventional structure that lacks links and joints. Hence, standard techniques like the Denavit-Hartenberg (D-H) algorithm cannot be directly applied for developing continuum arm kinematics. Moreover, the design of each continuum arm varies with respect to the flexible backbone present in the system, the positioning, type and number of actuators. The constraints imposed by these factors make the set of reachable configurations and nature of movements unique to every continuum robot. This makes it difficult to formulate generalized kinematic or dynamic models for continuum robot hardware. Chirikjian and Burdick were the first to introduce a method for modeling the kinematics of a continuum structure by representing the curve-shaping function using modal functions [6]. Mochiyama used the Serret- Frenet formulae to develop kinematics of hyper-degrees of freedom continuum manipulators [5]. For details on the previously developed and more manipulator-specific kinematics of the Rice/Clemson "Elephant trunk" manipulator, see [1- 11]. For the Air Octor and Octarm continuum robots, more general forward and inverse kinematics have been developed by incorporating the transformations of each section of the manipulator (using D-H parameters of an equivalent virtual rigid link robot) and expressing those in terms of the continuum manipulator section parameters [4]. The net result of the work in [3-6] is the establishment of a general set of kinematic algorithms for continuum robots. Thus, the kinematics (i.e. geometry based modeling) of a quite general set of prototypes of continuum manipulators has been developed and basic control strategies now exist based on these. The development of analytical models to analyze continuum arm dynamics (i.e. physicsbased models involving forces in addition to geometry) is an active, ongoing research topic in this field. From a practical perspective, the modeling approaches currently available in the literature prove to be very complicated and a dynamic model which could be conveniently implemented in an actual device's real-time controller has not been developed yet. The absence of a computationally tractable dynamic model for these robots also prevents the study of interaction of external forces and the impact of collisions on these continuum structures. This impedes the study and ultimate usage of continuum robots in various practical applications like grasping and manipulation, where impulsive dynamics [1, 4] are important factors. Although continuum robotics is an interesting subclass of robotics with promising applications for the future, from the current state of the literature, this field is still in its stages of inception.

The main goal of this research are; design a modified fuzzy inference system and applied to sliding mode controller to eliminate the chattering based on fuzzy

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inference system, and design a modified tuning method to online tuning a modified artificial sliding mode controller to have a best performance in presence of uncertainty.

This paper is organized as follows; section 2, is served as an introduction to the sliding mode controller formulation algorithm and its application to control of continuum robot, fuzzy inference system, dynamic of continuum robot and proof of stability. Part 3, introduces and describes the methodology. Section 4 presents the simulation results and discussion of this algorithm applied to a continuum robot and the final section is describing the conclusion.

II. THEORY

A. Dynamic Formulation of Continuum Robot

The model resulting from the application of Lagrange's equations of motion obtained for this system can be represented in the form

$$F_{coeff}\ \underline{\tau} = D\left(\underline{q}\right)\underline{\ddot{q}} + C\left(\underline{q}\right)\underline{\dot{q}} + G\left(\underline{q}\right) \qquad (1)$$

where τ is a vector of input forces and q is a vector of generalized co-ordinates. The force coefficient matrix F_{coeff} transforms the input forces to the generalized forces and torques in the system. The inertia matrix, D is composed of four block matrices. The block matrices that correspond to pure linear accelerations and pure angular accelerations in the system (on the top left and on the bottom right) are symmetric. The matrix C contains coefficients of the first order derivatives of the generalized co-ordinates. Since the system is nonlinear, many elements of C contain first order derivatives of the generalized co-ordinates. The remaining terms in the dynamic equations resulting from gravitational potential energies and spring energies are collected in the matrix G. The coefficient matrices of the dynamic equations are given below,

$$Fcoeff = \qquad (2)$$

$$\begin{bmatrix} 1 & 1 & cos(\theta_1) & cos(\theta_1) & cos(\theta_1+\theta_2) & cos(\theta_1+\theta_2) \\ 0 & 0 & 1 & 1 & cos(\theta_2) & cos(\theta_2) \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 1/2 & -1/2 & 1/2 & -1/2 & 1/2+s_2 sin(\theta_2) & -1/2+s_2 sin(\theta_2) \\ 0 & 0 & 1/2 & -1/2 & 1/2 & -1/2 \\ 0 & 0 & 0 & 0 & 1/2 & -1/2 \end{bmatrix}$$

$$D\left(\underline{q}\right) = \qquad (3)$$

$$\begin{bmatrix} m_1+m_2+m_3 & m_2cos(\theta_1)+m_3cos(\theta_1) & m_3cos(\theta_1+\theta_2) & -m_2s_2sin(\theta_1)-m_3s_2sin(\theta_1)-m_3s_3sin(\theta_1+\theta_2) & -m_3s_3sin(\theta_1+\theta_2) & 0 \\ m_2cos(\theta_1)+m_3cos(\theta_1) & m_2+m_3 & m_3cos(\theta_2) & -m_3s_3sin(\theta_2) & -m_3s_3sin(\theta_2) & 0 \\ m_3cos(\theta_1+\theta_2) & m_3cos(\theta_2) & m_3 & m_3s_3sin(\theta_2) & 0 & 0 \\ -m_2s_2sin(\theta_1)-m_3s_2sin(\theta_1)-m_3s_3sin(\theta_1+\theta_2) & -m_3s_3sin(\theta_2) & m_3s_2sin(\theta_2) & m_2s_2^2+I_1+I_2+I_3+m_3s_2^2+m_3s_3^2+2m_3s_3cos(\theta_2)s_2 & I_2+m_3s_3^2+I_3+m_3s_3cos(\theta_2)s_2 & I_3 \\ -m_3s_3sin(\theta_1+\theta_2) & -m_3s_3sin(\theta_2) & 0 & I_2+m_3s_3^2+I_3+m_3s_3cos(\theta_2)s_2I & I_2+m_3s_3^2+I_3 & I_3 \\ 0 & 0 & 0 & I_3 & I_3 & I_3 \end{bmatrix}$$

$$C\left(\underline{q}\right) = \tag{4}$$

$$\begin{bmatrix}
c_{11}+c_{21} & \begin{matrix}-2m_2 sin(\theta_1)\dot{\theta}_1\\ -2m_3 sin(\theta_1)\dot{\theta}_1\end{matrix} & \begin{matrix}-2m_3 sin(\theta_1+\theta_2)\\ (\dot{\theta}_1+\dot{\theta}_2)\end{matrix} & \begin{matrix}-m_2 s_2\\ cos(\theta_1)(\dot{\theta}_1)\\ +(1/2)(c_{11}+c_{21})\\ -m_3 s_2\\ cos(\theta_1)(\dot{\theta}_1)\\ -m_3 s_3\\ cos(\theta_1+\theta_2)(\dot{\theta}_1)\end{matrix} & -m_3 s_3 sin(\theta_1+\theta_2) & 0\\
0 & c_{12}+c_{22} & \begin{matrix}-2m_3 sin(\theta_2)\\ (\dot{\theta}_1+\dot{\theta}_2)\end{matrix} & \begin{matrix}-m_3 s_3(\dot{\theta}_1)\\ +(1/2)\\ (c_{12}+c_{22})\\ -m_3 s_2(\dot{\theta}_1)\\ -m_3 s_3\\ cos(\theta_2)(\dot{\theta}_1)\end{matrix} & \begin{matrix}-2m_3 s_3\\ cos(\theta_2)(\dot{\theta}_1)\\ -m_3 s_3\\ cos(\theta_2)(\dot{\theta}_2)\end{matrix} & 0\\
0 & 2m_3 sin(\theta_2)(\dot{\theta}_1) & c_{13}+c_{23} & \begin{matrix}-m_3 s_3 s_2\\ cos(\theta_2)(\dot{\theta}_1)\\ -m_3 s_3(\dot{\theta}_1)\end{matrix} & \begin{matrix}-2m_3 s_3(\dot{\theta}_1)\\ -m_3 s_3(\dot{\theta}_2)\end{matrix} & \begin{matrix}(1/2)\\ (c_{13}+c_{23})\end{matrix}\\
\begin{matrix}(1/2)\\ (c_{11}+c_{21})\end{matrix} & \begin{matrix}2m_3 s_3 cos(\theta_2)(\dot{\theta}_1)\\ -2m_3 s_2(\dot{\theta}_1)\\ +2m_2 s_2(\dot{\theta}_1)\end{matrix} & \begin{matrix}2m_3 s_3(\dot{\theta}_1+\dot{\theta}_2)\\ -2m_3 s_2 cos(\theta_2)\\ (\dot{\theta}_1+\dot{\theta}_2)\end{matrix} & \begin{matrix}2m_3 s_3 s_2\\ sin(\theta_2)(\dot{\theta}_2)\\ +(1^2/4)\\ (c_{11}+c_{21})\end{matrix} & \begin{matrix}m_3 s_3 s_2\\ sin(\theta_2)(\dot{\theta}_2)\end{matrix} & 0\\
0 & \begin{matrix}(1/2)(c_{12}+c_{22})+\\ 2m_3 s_3 cos(\theta_2)(\dot{\theta}_1)\end{matrix} & \begin{matrix}2m_3 s_3\\ (\dot{\theta}_1+\dot{\theta}_2)\end{matrix} & \begin{matrix}m_3 s_3 s_2\\ sin(\theta_2)(\dot{\theta}_1)\end{matrix} & \begin{matrix}(1^2/4)\\ (c_{12}+c_{22})\end{matrix} & 0\\
0 & 0 & (1/2)(c_{13}-c_{23}) & 0 & 0 & \begin{matrix}(1^2/4)\\ (c_{13}+c_{23})\end{matrix}
\end{bmatrix}$$

$$G\left(\underline{q}\right) = \tag{5}$$

$$\begin{bmatrix}
-m_1 g - m_2 g + k_{11}(s_1+(1/2)\theta_1 - s_{01}) + k_{21}(s_1-(1/2)\theta_1 - s_{01}) - m_3 g\\
-m_2 g cos(\theta_1) + k_{12}(s_2+(1/2)\theta_2 - s_{02}) + k_{22}(s_2-(1/2)\theta_2 - s_{02}) - m_3 g cos(\theta_1)\\
-m_3 g cos(\theta_1+\theta_2) + k_{13}(s_3+(1/2)\theta_3 - s_{03}) + k_{23}(s_3-(1/2)\theta_3 - s_{03})\\
\begin{matrix}m_2 s_2 g sin(\theta_1) + m_3 s_3 g sin(\theta_1+\theta_2) + m_3 s_2 g sin(\theta_1) + k_{11}(s_1+(1/2)\theta_1 - s_{01})(1/2)\\ +k_{21}(s_1-(1/2)\theta_1 - s_{01})(-1/2)\end{matrix}\\
m_3 s_3 g sin(\theta_1+\theta_2) + k_{12}(s_2+(1/2)\theta_2 - s_{02})(1/2) + k_{22}(s_2-(1/2)\theta_2 - s_{02})(-1/2)\\
k_{13}(s_3+(1/2)\theta_3 - s_{03})(1/2) + k_{23}(s_3-(1/2)\theta_3 - s_{03})(-1/2)
\end{bmatrix}$$

B. *Sliding Mode Controller*

Consider a nonlinear single input dynamic system is defined by [12-35]:

$$x^{(n)} = f(\vec{x}) + b(\vec{x})u \tag{6}$$

Where u is the vector of control input, $x^{(n)}$ is the n^{th} derivation of x, $x = [x, \dot{x}, \ddot{x}, \dots, x^{(n-1)}]^T$ is the state vector, f(x) is unknown or uncertainty, and b(x) is of known sign function. The main goal to design this controller is train to the desired state; $x_d = [x_d, \dot{x}_d, \ddot{x}_d, \dots, x_d^{(n-1)}]^T$, and trucking error vector is defined by [36-44]:

$$\tilde{x} = x - x_d = [\tilde{x}, \dots, \tilde{x}^{(n-1)}]^T \tag{7}$$

A time-varying sliding surface $s(x,t)$ in the state space R^n is given by [45-56]:

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\, \tilde{x} = 0 \tag{8}$$

where λ is the positive constant. To further penalize tracking error, integral part can be used in sliding surface part as follows [57-69]:

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1} \left(\int_0^t \tilde{x}\, dt\right) = 0 \tag{9}$$

The main target in this methodology is kept the sliding surface slope $s(x,t)$ near to the zero. Therefore, one of the common strategies is to find input U outside of $s(x,t)$ [23].

$$\frac{1}{2}\frac{d}{dt}s^2(x,t) \le -\zeta|s(x,t)| \tag{10}$$

where ζ is positive constant.

$$\text{If } S(0)>0 \rightarrow \frac{d}{dt}S(t) \le -\zeta \tag{11}$$

To eliminate the derivative term, it is used an integral term from t=0 to t=t_{reach}

$$\int_{t=0}^{t=t_{reach}} \frac{d}{dt}S(t) \le -\int_{t=0}^{t=t_{reach}} \eta \rightarrow S(t_{reach}) - S(0) \le -\zeta(t_{reach} - 0) \tag{12}$$

Where t_{reach} is the time that trajectories reach to the sliding surface so, suppose $S(t_{reach} = 0)$ defined as;

$$0 - S(0) \le -\eta(t_{reach}) \rightarrow t_{reach} \le \frac{S(0)}{\zeta} \tag{13}$$

and

$$if\ S(0) < 0 \rightarrow 0 - S(0) \le -\eta(t_{reach}) \rightarrow S(0) \le -\zeta(t_{reach}) \rightarrow t_{reach} \le \frac{|S(0)|}{\eta} \tag{14}$$

Equation (14) guarantees time to reach the sliding surface is smaller than $\frac{|S(0)|}{\zeta}$ since the trajectories are outside of $S(t)$.

$$if\ S_{t_{reach}} = S(0) \rightarrow error(x - x_d) = 0 \tag{15}$$

suppose S is defined as

$$s(x,t) = (\frac{d}{dt} + \lambda)\ \ \tilde{x} = (\dot{x} - \dot{x}_d) + \lambda(x - x_d) \tag{16}$$

The derivation of S, namely, $\dot{S}$ can be calculated as the following;

$$\dot{S} = (\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d) \tag{17}$$

suppose the second order system is defined as;

$$\ddot{x} = f + u \ \rightarrow \dot{S} = f + U - \ddot{x}_d + \lambda(\dot{x} - \dot{x}_d) \tag{18}$$

Where f is the dynamic uncertain, and also since $S = 0\ and\ \dot{S} = 0$, to have the best approximation ,$\widehat{U}$ is defined as

$$\widehat{U} = -\hat{f} + \ddot{x}_d - \lambda(\dot{x} - \dot{x}_d) \tag{19}$$

A simple solution to get the sliding condition when the dynamic parameters have uncertainty is the switching control law [30-37]:

$$U_{dis} = \widehat{U} - K(\vec{x},t)\cdot \mathrm{sgn}(s) \tag{20}$$

where the switching function $\mathrm{sgn}(S)$ is defined as [16-29]

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{21}$$

and the $K(\vec{x},t)$ is the positive constant. Suppose by (10) the following equation can be written as,

$$\frac{1}{2}\frac{d}{dt}s^2(x,t) = \dot{S}\cdot S = \left[f - \hat{f} - K\mathrm{sgn}(s)\right]\cdot S = \left(f - \hat{f}\right)\cdot S - K|S| \tag{22}$$

and if the equation (14) instead of (13) the sliding surface can be calculated as

$$s(x,t) = (\frac{d}{dt} + \lambda)^2 \left(\int_0^t \tilde{x}\,dt\right) = (\dot{x} - \dot{x}_d) + 2\lambda(\dot{x} - \dot{x}_d) - \lambda^2(x - x_d) \tag{23}$$

in this method the approximation of U is computed as [32]

$$\widehat{U} = -\hat{f} + \ddot{x}_d - 2\lambda(\dot{x} - \dot{x}_d) + \lambda^2(x - x_d) \tag{24}$$

Based on above discussion, the variable structure control law for a multi degrees of freedom robot manipulator is written as [16-45]:

$$\tau = \tau_{eq} + \tau_{dis} \tag{25}$$

Where, the model-based component $\boldsymbol{\tau_{eq}}$ is the nominal dynamics of systems calculated as follows [44-69]:

$$\tau_{eq} = \left[D^{-1}(f + C + G) + \dot{S}\right]D \tag{26}$$

and $\boldsymbol{\tau_{dis}}$ is computed as [30-60];

$$\tau_{dis} = K\cdot \mathrm{sgn}(S) \tag{27}$$

By (27) and (26) the variable structure control of robot manipulator is calculated as;

$$\tau = \left[D^{-1}(f + C + G) + \dot{S}\right]D + K\cdot \mathrm{sgn}(S) \tag{28}$$

The lyapunov formulation can be written as follows,

$$V = \frac{1}{2}S^T.D.S \tag{29}$$

C. *Fuzzy Logic Methodology*

Based on foundation of fuzzy logic methodology; fuzzy logic controller has played important rule to design nonlinear controller for nonlinear and uncertain systems [23-37]. However the application area for fuzzy control is really wide, the basic form for all command types of controllers consists of; Input fuzzification (binary-to-fuzzy [B/F] conversion), Fuzzy rule base (knowledge base), Inference engine and Output

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defuzzification (fuzzy-to-binary [F/B] conversion). Figure 1 shows the fuzzy controller part.

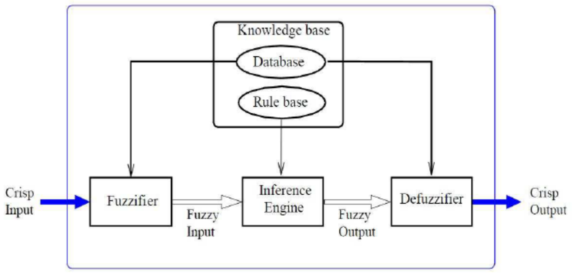

Figure 1: Fuzzy inference system

The fuzzy inference engine offers a mechanism for transferring the rule base in fuzzy set which it is divided into two most important methods, namely, Mamdani method and Sugeno method. Mamdani method is one of the common fuzzy inference systems and he designed one of the first fuzzy controllers to control of system engine. Mamdani's fuzzy inference system is divided into four major steps: fuzzification, rule evaluation, aggregation of the rule outputs and defuzzification. Michio Sugeno use a singleton as a membership function of the rule consequent part. The following definition shows the Mamdani and Sugeno fuzzy rule base [22-33]

$$\begin{array}{l} if\ x\ is\ A\ and\ y\ is\ B\ then\ z\ is\ C\ 'mamdani' \\ if\ x\ is\ A\ and\ y\ is\ B\ then\ z\ is\ f(x,y)'sugeno' \end{array} \quad (30)$$

When x and y have crisp values fuzzification calculates the membership degrees for antecedent part. Rule evaluation focuses on fuzzy operation (AND/OR) in the antecedent of the fuzzy rules. The aggregation is used to calculate the output fuzzy set and several methodologies can be used in fuzzy logic controller aggregation, namely, Max-Min aggregation, Sum-Min aggregation, Max-bounded product, Max-drastic product, Max-bounded sum, Max-algebraic sum and Min-max. Defuzzification is the last step in the fuzzy inference system which it is used to transform fuzzy set to crisp set. Consequently defuzzification's input is the aggregate output and the defuzzification's output is a crisp number. Centre of gravity method (COG) and Centre of area method (COA) are two most common defuzzification methods.

III. METHODOLOGY

In the proposed method fuzzy rule base was designed to have a nonlinear sliding surface slope function.

The fuzzy system can be defined as below

$$f(x) = \tau_{fuzzy} = \sum_{l=1}^{M} \theta^T \zeta(x) = \psi(e,\dot{e}) \quad (31)$$

where $\theta = (\theta^1, \theta^2, \theta^3, \dots\dots, \theta^M)^T, \zeta(x) = (\zeta^1(x), \zeta^2(x), \zeta^3(x), \dots\dots, \zeta^M(x))^T$

$$\zeta^1(x) = \frac{\sum_i \mu_{(xi)} x_i}{\sum_i \mu_{(xi)}} \quad (32)$$

where $\theta = (\theta^1, \theta^2, \theta^3, \dots\dots, \theta^M)$ is adjustable parameter in (31) and $\mu_{(xi)}$ is membership function.
error base fuzzy controller can be defined as

$$\tau_{fuzzy} = \psi(e,\dot{e}) \quad (33)$$

To eliminate the chattering fuzzy inference system is used instead of saturation and/or switching function. Design a nonlinear sliding function has five steps:

1. ***Determine inputs and outputs:*** This controller has one input (S) and one output (α). The input is sliding function (S) and the output is coefficient which estimate the saturation function (α).
2. ***Find membership function and linguistic variable:*** The linguistic variables for sliding surface (S) are; Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB), and the linguistic variables to find the saturation coefficient (α) are; Large Left (LL), Medium Left (ML), Small Left (SL), Zero (Z), Small Right (SR), Medium Right (MR), Large Right (LR).
3. ***Choice of shape of membership function:*** In this work triangular membership function was selected.
4. ***Design fuzzy rule table:*** design the rule base of fuzzy logic controller can play important role to design best performance for proposed method, suppose that two fuzzy rules in this controller are

F.R[1]: *IF S is Z, THEN α is Z.* (34)
F.R[2]: *IF S is (PB) THEN α is (LR).*

The complete rule base for this controller is shown in Table 1.

TABLE 1: Rule table for proposed method

S	NB	NM	NS	Z	PS	PM	PB
τ	LL	ML	SL	Z	SR	MR	LR

The control strategy that deduced by Table1 are

- ➢ If sliding surface (S) is N.B, the control applied is N.B for moving S to S=0.
- ➢ If sliding surface (S) is Z, the control applied is Z for moving S to S=0.

5. ***Defuzzification:*** The final step to design fuzzy logic controller is deffuzification , there are many deffuzzification methods in the literature, in this controller the COG method will be used, where this is given by

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$$COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} . \mu_u(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^{r} . \mu_u(x_k, y_k, U_i)} \quad (35)$$

$$if\ S = 0\ then\ \dot{-e} = \lambda e \quad (36)$$

the fuzzy division can be reached the best state when $S.\dot{S} < 0$ and the error is minimum by the following formulation

$$\theta^* = \arg\min [Sup_{x \in U} | \sum_{l=1}^{M} \theta^T \zeta(x) - \tau_{equ} |] \quad (37)$$

Where θ^* is the minimum error, $\sup_{x \in U} | \sum_{l=1}^{M} \theta^T \zeta(x) - \tau_{equ} |$ is the minimum approximation error. Figure 2 shows the fuzzy instead of saturation function.

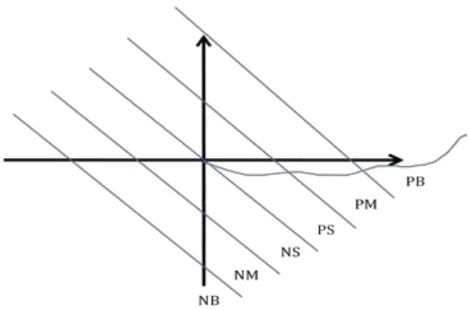

Figure 2: Nonlinear fuzzy inference system instead of saturation function

The system performance in proposed method is sensitive to sliding surface slope, λ. Thus, determination of an optimum λ value for a system is an important problem. If the system parameters are unknown or uncertain, the problem becomes more highlighted. This problem may be solved by adjusting the surface slope and sliding coefficient of the sliding mode controller continuously in real-time. This section focuses on, self tuning gain updating factor for two most important factor in proposed method, namely, sliding surface slop (λ) and sliding coefficient (K). Self tuning-proposed method has strong resistance and can solve the uncertainty problems. The block diagram for this method shows in Figure 3. In this controller the actual sliding surface gain (λ) is obtained by multiplying the sliding surface with gain updating factor(α). The gain updating factor (α) is calculated on-line by fuzzy dynamic model independent which has sliding surface (S) as its inputs. The gain updating factor is independent of any dynamic model of robotic manipulator parameters. Assuming that $\alpha = 1$, following steps used to tune the controller: adjust the value of λ and α to have an acceptable performance for any one trajectory by using trial and error.

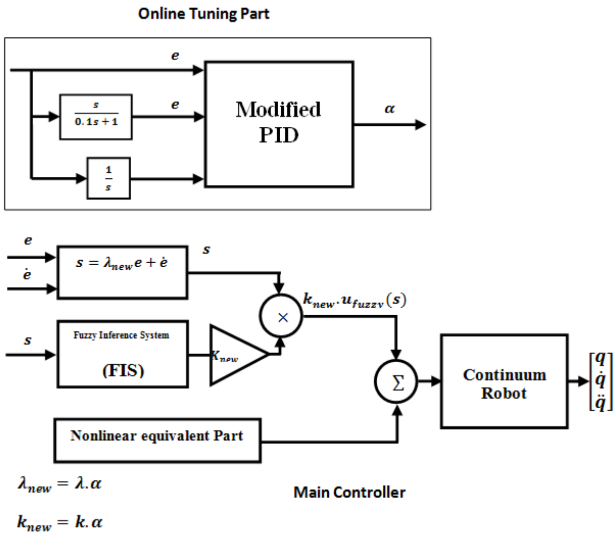

Figure 3: Block diagram of proposed artificial chattering free self tuning fuzzy sliding mode controller with minimum rule base in fuzzy equivalent part and fuzzy supervisory.

The online controller is used to find the minimum errors of $\theta - \theta^*$.

suppose K_j is defined as follows

$$K_j = \frac{\sum_{l=1}^{M} \theta_j^l [\mu_A(S_j)]}{\sum_{l=1}^{M} [\mu_A(S_j)]} = \theta_j^T \zeta_j(S_j) \quad (38)$$

Where $\zeta_j(S_j) = [\zeta_j^1(S_j), \zeta_j^2(S_j), \zeta_j^3(S_j), \ldots\ldots, \zeta_j^M(S_j)]^T$

$$\zeta_j^1(S_j) = \frac{\mu_{(A)}{}_j^l(S_j)}{\sum_i \mu_{(A)}{}_j^l(S_j)} \quad (39)$$

the adaption low is defined as

$$\dot{\theta}_j = \gamma_{sj} S_j \zeta_j(S_j) \quad (40)$$

where the γ_{sj} is the positive constant.
Based on online tuning of these two coefficient;

$$\lambda_{new} = \lambda.\alpha\ and\ K_{new} = K.\alpha \quad (41)$$

The dynamic equation of robot manipulator can be written based on the sliding surface as;

$$M\dot{S} = -VS + M\dot{S} + VS + G - \tau \quad (42)$$

It is supposed that

$$S^T(\dot{M} - 2V)S = 0 \quad (43)$$

it can be shown that

$$M\dot{S} + (V + \lambda)S = \Delta f - K \tag{44}$$

where $\Delta f = [M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q)] - \sum_{l=1}^{M} \theta^T \zeta(x)$

as a result $\dot{V}$ is became

$$\begin{aligned}
\dot{V} &= \frac{1}{2} S^T \dot{M} S - S^T V S + \sum \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j \\
&= S^T(-\lambda S + \Delta f - K) + \sum \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j \\
&= \sum_{j=1}^{m} [S_j (\Delta f_j - K_j)] - S^T \lambda S + \sum \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j \\
&= \sum_{j=1}^{m} [S_j (\Delta f_j - \theta_j^T \zeta_j(S_j))] - S^T \lambda S + \sum \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j \\
&= \sum_{j=1}^{m} [S_j (\Delta f_j - (\theta_j^*)^T \zeta_j(S_j) + \phi_j^T \zeta_j(S_j))] - S^T \lambda S \\
&\qquad + \sum \frac{1}{\gamma_{sj}} \phi_j^T \dot{\phi}_j \\
&= \sum_{j=1}^{m} [S_j (\Delta f_j - \left((\theta_j^*)^T \zeta_j(S_j)\right)] - S^T \lambda S)] \\
&\qquad + \sum (\frac{1}{\gamma_{sj}} \phi_j^T [\gamma_{sj} \zeta_j(S_j) S_j + \dot{\phi}_j])
\end{aligned}$$

where $\dot{\theta}_j = \gamma_{sj} S_j \zeta_j(S_j)$ is adaption law, $\dot{\phi}_j = -\dot{\theta}_j = -\gamma_{sj} S_j \zeta_j(S_j)$,

consequently $\dot{V}$ can be considered by

$$\dot{V} = \sum_{j=1}^{m} [S_j \Delta f_j - \left((\theta_j^*)^T \zeta_j(S_j)\right)] - S^T \lambda S \tag{45}$$

the minimum error can be defined by

$$e_{mj} = \Delta f_j - \left((\theta_j^*)^T \zeta_j(S_j)\right) \tag{46}$$

$\dot{V}$ is intended as follows

$$\begin{aligned}
\dot{V} &= \sum_{j=1}^{m} [S_j\, e_{mj}] - S^T \lambda S \\
&\le \textstyle\sum_{j=1}^{m} |S_j||e_{mj}| - S^T \lambda S \\
&= \sum_{j=1}^{m} |S_j||e_{mj}| - \lambda_j S_j^2 \\
&= \sum_{j=1}^{m} |S_j|(|e_{mj}| - \lambda_j S_j)
\end{aligned} \tag{47}$$

For continuous function $g(x)$, and suppose $\varepsilon > 0$ it is defined the fuzzy logic
system in form of (36) such that

$$Sup_{x \in U} |f(x) - g(x)| < \epsilon \tag{48}$$

the minimum approximation error (e_{mj}) is very small.

$$if\ \lambda_j = \alpha \quad that \quad \alpha|S_j| > e_{mj}\ (S_j \neq 0) \quad then \quad \dot{V} < 0\ for\ (S_j \neq 0) \tag{49}$$

IV. RESULTS AND DISCUSSION

Classical sliding mode control (SMC), and proposed method are implemented in Matlab/Simulink environment. Different sliding surface slope performance, tracking performance and robustness are compared.

5.1 Changing Sliding Surface Slope performance

For various value of sliding surface slope (λ) in SMC and proposed method the trajectory performances shows in Figures 4 and 5.

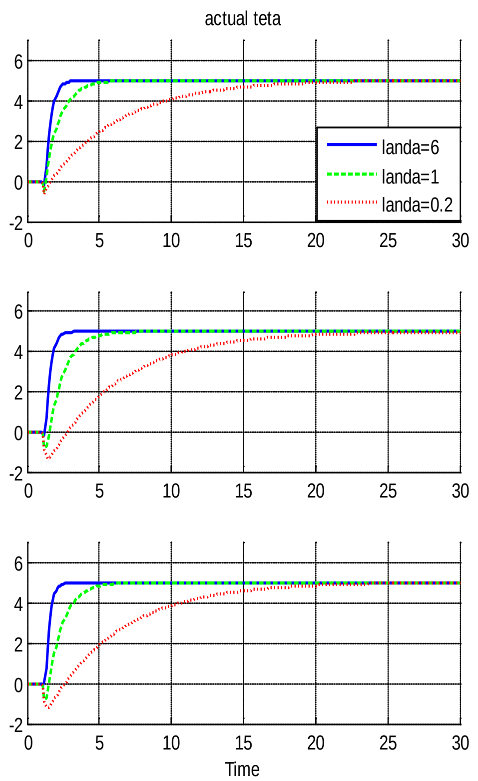

Figure 4: SMC trajectory performance, first; second and third link

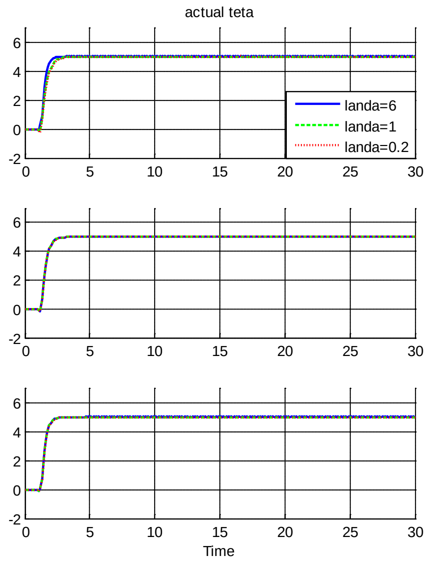

Figure 5: proposed method trajectory performance, first; second and third link

Figures 4 and 5 are shown trajectory performance with different sliding function for, sliding mode controller and proposed method. It is shown that the sensitivity in proposed method to sliding function is lower than SMC.

5.2 *Tracking performances*

From the simulation for first, second, and third trajectory without any disturbance, it can be seen that proposed method and classical SMC have same performance. This is primarily due to the constant parameters in simulation. Figure 6 shows tracking performance in certain system for SMC and proposed method.

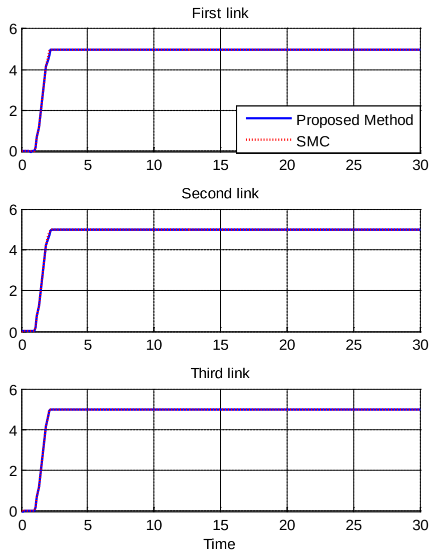

Figure 6: Trajectory performance: proposed method and SMC (first; second and third link)

5.3 Disturbance Rejection:

A band limited white noise with predefined of 30% the power of input signal is applied to the response. Figure 7 shows disturbance rejection for proposed method and SMC.

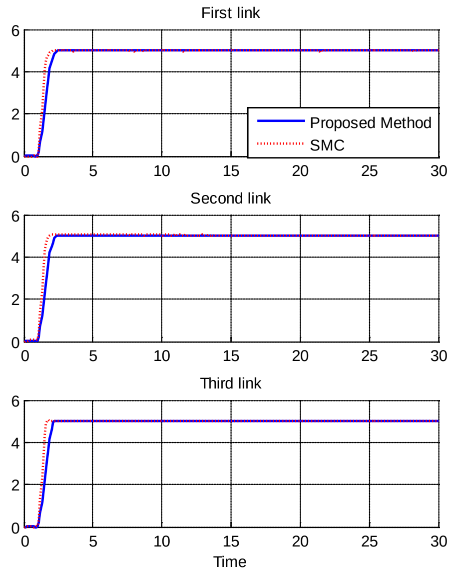

Figure 7: Disturbance rejection: proposed method and SMC (first; second and third link)

5.4 Errors in the model

Based on comparison between sliding mode controller and proposed method it is obvious that the error rate in SMC without and with noise are very different so this controller is not robust. Proposed methodology is more robust than SMC based on rate of error in presence of disturbance and without disturbance and in both situation the error is equal to zero.

TABLE 2: RMS Error Rate of Presented controllers

RMS Error Rate	SMC	Proposed method
Without Noise	1e-3	1e-7
With Noise	0.012	1.12e-6

V. CONCLUSION

Refer to the research, a 7 rules Mamdani's new on-line chattering free sliding mode controller and this suitability for use in the control of continuum robot manipulator has proposed in order to design high performance nonlinear controller in the presence of uncertainties and external disturbances. Sliding mode control methodology is selected as a frame work to construct the control law and address the stability and robustness of the close-loop system. The proposed approach effectively combines the design techniques from sliding mode control, fuzzy logic and adaptive control to improve the performance (e.g., trajectory, disturbance rejection, error and chattering) and enhance the robustness property of the controller. Each method

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by adding to the previous controller has covered negative points. The system performance in sliding mode controller is sensitive to the sliding function. Therefore, compute the optimum value of sliding function for a system is the important which this problem has solved by adjusting surface slope of the sliding function continuously in real-time. The chattering phenomenon is estimated by fuzzy method when estimate the saturation/switching function with 7 rule base. In this way, the overall system performance has improved with respect to the classical sliding mode controller. This controller solved chattering phenomenon as well as mathematical nonlinear equivalent part by applied modified supervisory method in new sliding mode controller.

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